A DEVELOPMENTAL CW FM MULTI-TARGET RADAR

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THESIS

A DEVELOPMENTAL

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by

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A Developmental

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ABSTRACT

The feasibility of an X-band (8.0-12.5 GHz) continuous-wave multiple-target radar employing linear frequency modulation was investigated.

From available laboratory equipment a working model was constructed and tested. Separate parabolic antennas were used for transmitting and receiving. The transmitter employs a reflex klystron followed by low and high-level traveling-wave tubes. The receiver utilizes a single narrow-band crystal filter with a swept local oscillator for range search.

Target data acquired with the developmental unit is presented.

TABLE OF CONTENTS

LIST OF FIGURES

TABLE OF SYMBOLS

Δf	transmitter frequency excursion
f_b	beat frequency
f_d	doppler shift frequency
f_f	bandwidth of range filter
f_o	center RF frequency
f_r	transmitter sweep repetition rate
R	target range
ΔR	range discrimination
T	transmitter frequency sweep period
Δt	time delay of echo (2R/C)
v_r	relative radial velocity

I. INTRODUCTION

Continuous-wave frequency-modulated radar may be defined as radar in which a continuous-wave transmission is frequency-modulated in a known manner and correlated to the return signal in order to obtain range information.

The earliest use of this type of system was by Appleton and Barnett in 1924 [1] when they wished to obtain evidence of the existence of the ionosphere.

Since 1924, the principle of single-target frequency-modulated radar has been used in aircraft altimeters. This type of altimeter came into use during World War II [2, 3] and is in widespread use today. Little work was done on FM multi-target systems until 1940 when some developments were made in England [4, 5] and in the United States. In 1955-1959 Keep [6], Tucker [7], Kay [8] and others applied the FM technique with better success. Still they concluded that a multi-target system would have to await the development of such devices as X-band amplifiers. In 1965 Barry and Fenwick of Stanford University [9] demonstrated the improvement of a linear frequency-modulated pulse ionogram over a pulsed sounder. Two advantages of CW FM are higher average power for the same peak power and less vulnerability to narrow-band interference.

Recent developments in solid-state technology have produced devices and equipment that permit the construction of a practical

multi-target CW FM radar. The most obvious applications of this type of system would be in situations where light weight, low power consumption, and high reliability are of paramount importance. Light weight requires operation at X-band or higher frequencies to obtain narrow antenna beamwidth with reasonable antenna size.

Problems requiring further development include optimum solid state circuitry for the complete system, and a duplexing system that will permit the use of a single antenna.

II. GENERAL THEORY OF FM RADAR

A. PRINCIPLES OF OPERATION

A conventional pulse radar transmits a short pulse to obtain good range resolution. In order to prevent range anbiguities, the pulse repetition period must be at least equal to the delay of the signal from the most distant detectable target. The above restriction results in two shortcomings of the conventional pulse radar. First, since the pulse width and pulse repetition frequency are constrained, the average transmitted power can be increased only by increasing the peak transmitted power.

The above-mentioned limitation of pulse radar can be overcome by the use of CW radar. In the case of a CW radar, the average power is equal to the peak power.

1. Determination of Distance

Figure 1 illustrates a simplified block diagram of an FM radar. Basically, energy taken from the transmitter is heterodyned with the echo signal. The difference frequency is directly proportional to distance. The relationship between the transmitted and received frequency with linear FM is illustrated in Figure 2. Using linear sawtooth modulation, the beat frequency is given by

$$f_b = \frac{df}{dt} \Delta t$$

where df/dt is the transmitter frequency excursion per transmitter frequency sweep period ($\Delta f/T$), t is the signal transit time (2R/C) and C is the velocity of light. Substitution gives the range equation.

$$R = \frac{C f_b T}{2 \Delta f}$$

In order to distinguish between targets at different ranges, a set of frequency filters of bandwidth f_r with center frequencies equally spaced may be used. Such a set of filters is used in what is known as a multi-filter receiver.

As seen in Figure 3, for a single target illuminated for an interval of time equal to or less than one sweep period, T, the spectrum out of the mixer is continuous and is centered about f_b. The spectrum has a bandwidth between nulls of $2/(T - \Delta t)$. The range resolution will be limited by the target spectral bandwidth if the filter bandwidth is equal to or less than this amount, but will be limited by the filter bandwidth if it is greater than this. With range resolution limited by spectral bandwidth, the approximate equation for range resolution is given by

$$\Delta R \approx \frac{C\,T}{2 \Delta f (T - \Delta t)}$$

If $\Delta t << T$, this becomes

$$\Delta R \approx \frac{C}{2 \Delta f}$$

This is equivalent to the range resolution of a pulse radar having the same transmitter bandwidth. With a CW FM radar the range

resolution can be changed simply by changing Δf without changing anything else. In a pulse radar both the transmitted pulse width and the IF bandwidth would have to be changed.

During the flyback of the frequency modulation, false signals will be produced if the flyback time is finite. To avoid this in the developmental system, the transmitter is suppressed during flyback.

Because the doppler frequency shift adds to or subtracts from the beat frequency (depending on the relative motion of the target and the sign of the slope of the frequency sweep), the indicated range of a moving target will be inaccurate. The doppler frequency shift, f_d, is given by

$$f_d = - \frac{2 v_r f_o}{C}$$

where v_r is the relative radial velocity and f_o is the center RF frequency. For a relative velocity of 30 knots, the doppler shift at 9 GHz is approximately 900 Hz. It follows from the above equation and Figure 2 that the range error due to target motion is

$$\Delta R = \frac{T v_r f_o}{\Delta f}$$

For a 9 GHz radar with T = 380 microseconds and Δf = 12 MHz, the range error is only 16 yards for a 100 knot relative radial velocity. This is of little importance for a system that is designed primarily for surface search, harbor and river navigation.

2. Examination of the Spectrum

In a FM radar system with linear sawtooth modulation, the transmitted wave is a CW signal of constant amplitude and linearly changing frequency. Normally the transmit signal is considered repetitive with repetition time T, and its Fourier transform consists of a spectrum of lines evenly spaced at intervals of the repetition time. However, with a free running oscillator where the phasing of the RF is not coherent from sweep to sweep, the transmit signal is not repetitive, and the transmit and receive spectrum is not a line spectrum but rather a continuous spectrum.

Since the sawtooth modulating waveform does not have instantaneous flyback, the transmit spectrum is as in Figure 10 and the received signal out of the mixer consists of two beat notes (Figure 2, 3). This leads to a range ambiguity which is peculiar to FM systems. However if the transmitter is pulsed off during the flyback time Figure 4a, 9) the transmit spectrum is as seen in Figure 11 and the second beat note ambiguity vanished as illustrated in Figure 4b. With the type of system mentioned, the received spectrum is continuous with a single beat note (f_b) for each point target and side lobes as seen in Figure 3.

Three other types of range ambiguity are present in a CW FM system: second time around echoes, doppler frequency shift, and finite bandwidth of the received beat note along with its side lobes. The first of these can be minimized in the same way as with pulse radars by making T large compared to the maximum expected echo time. The

range error due to doppler shift was discussed in the previous section. As seen in Figure 3, the range resolution is determined by either the spectrum width or the filter width, whichever is wider. If the spectrum width determines the range resolution, the range resolution deteriorates slightly with increasing range. It is seen in Figure 3 that the received spectrum contains a main lobe and side lobes. The side lobes may be mistaken for other targets if the filter bandwidth is equal to or less than the repetition frequency. The first pair of these side lobes are 13.2 db below the main lobe [10]. They may be further reduced in amplitude by amplitude modulating in appropriate fashion the transmitted signal amplitude or receiver gain, or by using a weighted receiver filter characteristic in a manner analogous to the technique used in chirp radars [11].

3. Considerations of Single-Gate FM Radar Systems

The possibility of attaining high range resolution is very pertinent to the navigational field, particularly for short range working such as navigating narrow waterways. The use of a multi-gate receiver would result in a large and complicated set compared to a normal pulse radar, particularly when the resolution is high and the maximum range is large. This draw-back has led to the exploration and use of the single-sweeping-gate FM radar system which sacrifices information rate for size and simplicity of design. However in the future, small solid-state multi-gate receivers may become available.

In a single-gate system, the beat notes corresponding to the various ranges are either scanned across a single fixed-frequency gate, or the filter frequency is varied. Since range is now being scanned it is obvious that the overall data rate must decrease or the sensitivity be lowered. Once range resolution has been determined, the range-frequency scanning rate, df_b/dt, should be about the same as the square of range filter bandwidth $(f_f)^2$. For maximum sensitivity, the range filter bandwidth ratio should be matched to the modulation repetition rate. To increase the data rate the modulation repetition rate can be increased and the bandwidth of the receiver filter increased.

Increase in the modulation repetition rate is limited by the occurrence of second-trace echoes and is therefore mainly applicable to short range scales. Use of a receiver bandwidth larger than the optimum is undesirable since range resolution would be impaired. For example, with ($\Delta t << T$), $f_f = 1/T$ and Δf = 12 MHz

$$\Delta R \approx \frac{C}{2\,\Delta f} = 14 \text{ yds.}$$

If the filter size is doubled, then range resolution is limited by filter bandwidth, and is given by

$$\Delta R \approx \frac{C\, f_f\, T}{2\,\Delta f}$$

The range resolution deteriorates to 28 yards, twice as much as with the narrower filter.

B. COMPARISON BETWEEN PULSE AND FM RADARS

It can be shown theoretically that an FM radar with a multi-gate receiver is equivalent in performance to a pulse radar having the same average power and utilizing the same bandwidth, antenna beamwidths, scanning speeds, operating frequency, receiver noise figure and other performance factors [12].

However some important differences in implementation are apparent between pulse and FM radar techniques. FM radar transmits CW power and is therefore not concerned with high peak powers. This difference becomes extremely important when the equivalent pulse set has peak powers approaching, or greater than that which the waveguide system can tolerate without breakdown. In pulse radar a duplexer provides isolation between transmitter and receiver to prevent receiver burn out or excess receiver dead time following the transmitted pulse. In CW FM radar, isolation is required to prevent transmitter noise from reducing sensitivity and to prevent receiver saturation. Isolation can be achieved by use of two antennas or any suitable duplexing method [13].

In FM radar the wide bandwidth necessary to attain the desired range resolution is only required at RF frequencies while in pulse radar wide bandwidth is also required in the IF amplifier. This sets a practical limit to the range resolution attainable with pulse techniques. However it should be noted that to take advantage of the higher range resolutions possible with the FM technique, a high degree of modulation linearity is required [10]. If the FM system uses a bank of parallel filters in

the receiver, the number required would have to be equal to the total number of range intervals to be resolved. Special display techniques are required if a display of the conventional type is desired. A range display can be obtained from the single filter FM system simply by effectively sweeping the filter across the received spectrum as has been discussed. This convenience arises as a result of the linear-frequency sweep. A fixed time delay $\Delta t = 2R/C$ corresponds to a fixed difference frequency, f_b, where

$$f_b = \frac{df}{dt} \Delta t$$

The spectrum (amplitude-frequency) of the received signal out of the mixer thus becomes the normal A-scope (amplitude-range) display. Finally, the relative immunity to narrow-band interference that frequency modulation systems enjoy over amplitude modulated systems is retained.

III. GENERAL ASPECTS OF FM RADAR APPARATUS

A. TRANSMITTING OSCILLATORS AND THEIR MODULATION

At frequencies higher than about 3 GHz, reflex klystrons are a convenient signal source. The frequency of oscillation of the klystron oscillator is determined by the resonant frequency of the cavity and the magnitude of the repeller voltage. By simply changing the repeller voltage the frequency can be modulated over the range required for a CW FM radar. However one drawback is its relatively low efficiency.

Indications are that in the very near future cheaper solid-state sources will be available with adequate power and higher efficiency to replace the klystron.

In all FM oscillators frequency modulation is always combined with some incidental amplitude modulation which may be excessive when wide-frequency deviations are required. With the frequency deviations needed for FM radar, amplitude modulation is not a problem.

B. ANTENNAS AND THE FEED-THROUGH PROBLEM

Due to noise in the transmitter of an FM radar, it may be difficult to detect weak target echoes if a single antenna is used for both transmission and reception. Two separate antennas are more practical, and precautions should be taken to prevent transmitted energy from passing directly from the transmitting to the receiving antennas.

The coupling or leakage between the transmitting and receiving antennas gives the same result as a stationary target at essentially zero range. Strong coupling may produce receiver overloading and hence mask weak target signals.

For X-band, high directivity can be obtained with moderate aperature size. Good isolation between two antennas is relatively easy to obtain when their directivity is high, and very little shielding between antennas is necessary.

C. RECEIVING EQUIPMENT

In the design of any radar receiver, special care should be taken to suppress noise which may be developed at its input and which has a frequency spectrum falling within the amplification response of the receiver. The main source of this noise in the CW FM receiver is the FM noise associated with the transmitter and the local oscillator.

The difference frequency in the FM radar is obtained by mixing the received signal with a local signal obtained directly from the transmitter. Undesirable amplitude modulation may accompany the frequency-modulation process. Possible sources of this amplitude modulation include non-uniform frequency response in the input tank circuit of the mixer (Figure 5), in the transmitter output, and in the frequency translation system of the superheterodyne receiver.

The resulting amplitude modulation is periodic at the modulation rate and may or may not be sinusoidal in nature.

In the developmental system this type of interference is present. However, with a little care in alignment and adjustment its amplitude can be made negligible.

IV. DEVELOPMENTAL FM RADAR

A. SYSTEM ANALYSIS

The system as illustrated in Figure 5 employs an RF signal generator linearly frequency modulated by a sawtooth waveform (Figure 8). The RF frequency is centered at 9 GHz with a total frequency deviation of 12 MHz. This spectrum is then mixed with a 30 MHz signal and passed through an upper side-band filter. The result is a spectrum centered about 9.03 GHz with 12 MHz frequency deviation. This signal is amplified by low and high-level broad-band traveling-wave tubes. The high level TWT is pulsed on and off in synchronism with the modulating sawtooth as shown in Figure 9 to eliminate spurious signals associated with the frequency retrace. Two circular parabolic antennas with 3 degree beamwidths are used for transmitting and receiving.

In order to determine range, a portion of the output from the signal generator is fed through a band-pass filter and introduced into the receiver mixer. The signal introduced into the mixer is thereby offset 30 MHz with respect to the transmitted signal. Since the antennas are physically located one above the other and there is some leakage between them, a 30 MHz signal representing zero range appears at the output of the IF preamplifier. Because of the positive slope of the modulation sawtooth applied to the repeller of the reflex klystron, the output of the RF generator sweeps down in frequency. This results in the received signal being higher in frequency at any instant than the transmitted

signal. Therefore the received signal out of the mixer is nominally 30 MHz plus the frequency difference (f_b) resulting from the range delay for each target in the antenna beam. Thus the IF signal for zero range is a nominal 30 MHz, while the signal frequency associated with other targets increases in direct proportion to range. If the frequency of the IF signal generator is slowly decreased from 30 MHz, this total target spectrum is translated down in frequency so that first the zero-range signal appears in the passband of the 30 MHz crystal filter, and then in succession signals associated with targets at greater ranges.

The output of the 3.8 KHz wide crystal filter is amplified, detected, and applied to the vertical plates of an oscilloscope. It could also be used for intensity modulation of a planned position indicator (PPI) oscilloscope. Horizontal deflection of the oscilloscope is from the same low-frequency sawtooth generator which produces the slow frequency translation of the IF signal generator. The result is an "A" scope presentation.

A high-frequency radio receiver was used to amplify and detect the output of the crystal filter. Unfortunately, the only receivers available had automatic gain control (AGC) time constants that were too slow for the desired range sweep rates. The result of using a long AGC time constant is that an averaging process is inevitable and target definition is lost. Since a fully satisfactory receiver was not available, and time did not permit the development of a suitable receiver, most observations

of targets were made by examining the spectrum with a spectrum analyzer tuned to 30 MHz. This gave a very satisfactory "A" scope type of presentation.

B. EXPERIMENTAL RESULTS

Because of the narrow beamwidths of the two parabolic antennas and the fact that they must be trained independently in azimuth and elevation, it was very difficult to align them on a target. The two pencil beams must coincide for maximum target illumination. Microwave filter alignment and proper phasing of the blanking signal with respect to the transmitter frequency sweep is critical for proper system operation and range calibration. Drift of the signal generator frequency which was believed to be caused by line voltage fluctuations, was also a problem. Even with these difficulties and the limited field of view from the radar location in Spanagel Hall room 704, some very meaningful results illustrating the system's capabilities were obtained.

Examination of Figure 8 and Figure 12 demonstrates excellent correlation between the "A" trace presentation and the physical picture. The vertical alignment is such that the main portion of the beam is trained on Point Alones. If the beam is lowered, the echo from the Coast Guard Pier becomes much larger in amplitude. Sea clutter is obvious after the beach houses and after the boats and the Coast Guard Pier. This sea clutter disappears in the shadow beyond Point Cabrillo, and only thermal noise is obtained in this region. Figure 13 also shows

largely thermal noise since the antennas were directed to the sky. As can be seen from the amplitude of the zero-range leakage signal, the receiver gain has been greatly increased.

Figure 7 and Figure 14 illustrate a short-range capability. Ingersoll Hall is two stories higher than Halligan Hall and with the antennas trained on the former, it shows a larger return in spite of its greater range. The large return just after the initial Halligan Hall return is the windowed structure in the center of the building roof. The large target just after the initial Ingersoll Hall return is from a railing on the roof at the far side of the building.

V. CONCLUSIONS

It has been demonstrated that it is feasible to build a multi-target CW FM radar.

With state-of-the-art solid-state technology, many improvements are possible. These improvements include a solid-state linear FM oscillator to replace the reflex klystron traveling-wave-tube combination, an offset local oscillator that is phase-locked to the sum or difference of the transmitter and IF frequencies, and a solid-state IF amplifier with a fast time constant to react to narrow targets.

Range side lobes were not observed in the photographs. This is largely because the frequency analyzer utilizes Gaussian filters. Another method of reducing range side lobes is shown dotted in Figure 5. This addition of a balanced modulator fed by a pulse-forming network in phase with the transmitter frequency sweep would cosine modulate the receiver gain. This technique reduces the amplitude of the side bands accompanying the echo spectrum associated with each target at the IF frequency (Figure 3), and hence reduces the amplitude of the range side lobes [10].

APPENDIX A

EQUIPMENT LIST (FIGURE 5)

Synthesizer Driver, Hewlett Packard, 5110B.

Frequency Synthesizer, Hewlett Packard, 5105A.

Spectrum Analyzer, Tektronix Inc., 491.

Oscilloscope, Tektronix, Inc., 546.

Wide Band (DC-500KC 50 Watt) Amplifier, Krohn-Hite (Used to amplify modulation pulse for HP495A TWT).

HF VCG Generator, Wavetek, 142.

R-390A/URR IF Receiver, Copehart Corp.

Regulated Power Supply, Power/Mate Corp.

Pulse Generator, Data Pulse, 101.

RF Signal Generator (7.0-11.0 GHz), Polarod, 1108M4.

Low Level Broad Band Traveling Wave Tube, Varian.

Microwave Amplifier (7.0-12.4 GHz), Hewlett Packard, 495A.

Filter (8580-9600 MHz), Frequency Engineering Laboratory, 850CW.

Balanced Modulator (0.2-500 MHz), RELCOM, M1.

Uniline Isolator, Lewis and Kaufman Electronics Corp.

DA-138/TRM-3 Crystal Detector.

X-Band Airborne Parabolic Reflectors, 20-inch for transmit, 18-inch for receive.

Crystal Mixer (8.5-9.6 KMHz) and 30 MHz Preamplifier, Varian, XBH-7.

Crystal Mixer, Serial No. 1-2-101, USNPGS.

Crystal IF Filter, Damon, 6647A.

APPENDIX B

RADAR CHARACTERISTICS

TRANSMITTER:

POWER OUT	2 Watts Maximum
FREQUENCY DEVIATION	12 MHz Maximum
SWEEP PERIOD	380 Microseconds
SWEEP RETRACE TIME (TRANSMITTER OFF)	20 Microseconds
CARRIER FREQUENCY	9.00 GHz

RECEIVER:

RECEIVER NOISE FIGURE	13.8 db
IF BANDWIDTH	3.8 KHz (3 db)
SHAPE FACTOR	60/6 = 3.7:1
IF CENTER FREQUENCY	30,000,015 Hz

ANTENNA CHARACTERISTICS:

RECEIVER	18 inch circular parabolic reflector, approximately 3 degree beamwidth.
TRANSMITTER	20 inch parabolic reflector, approximately 3 degree beamwidth.

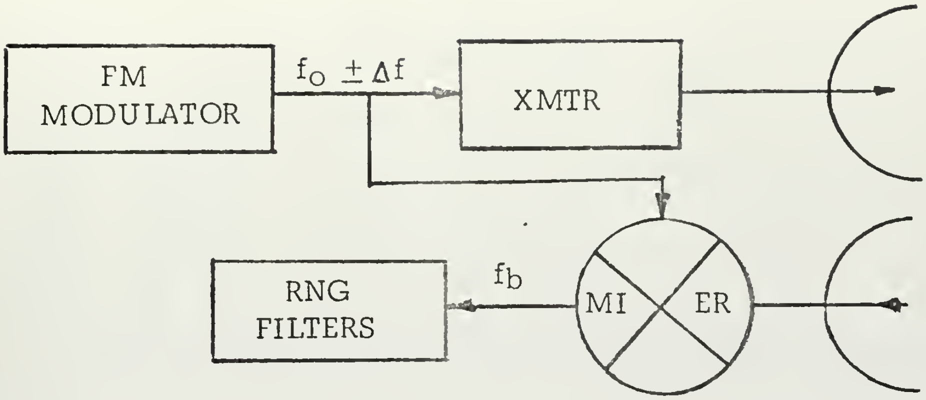

Figure 1.

Linear FM homodyne radar.

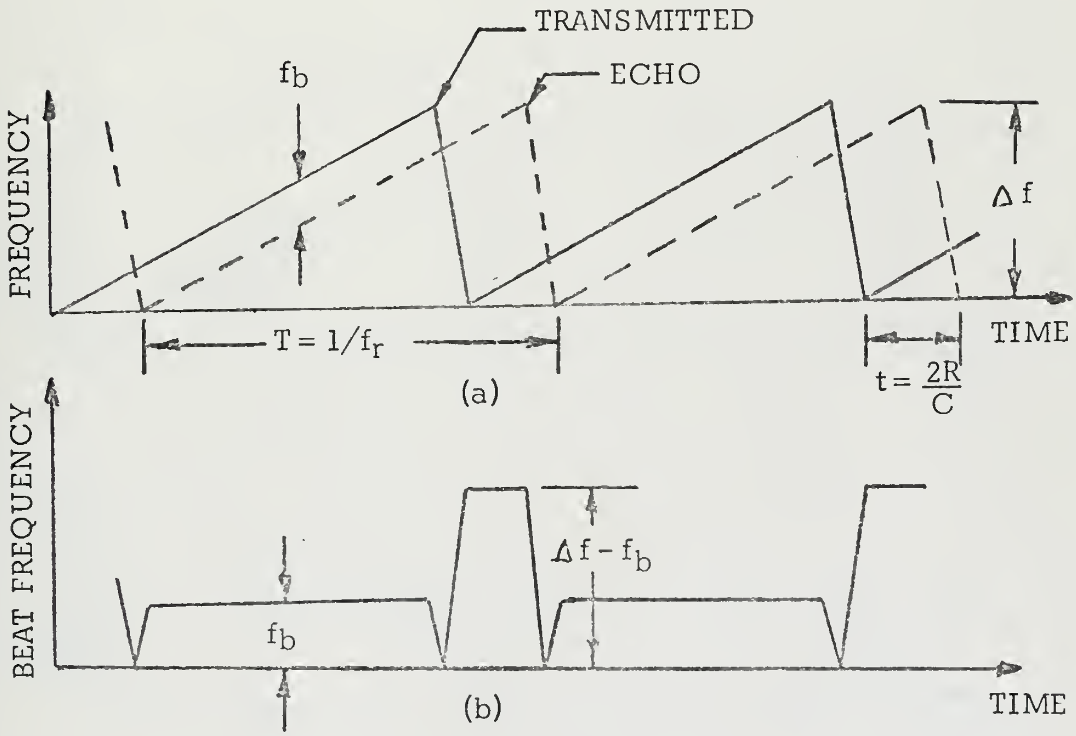

Figure 2.

Method of obtaining echo signals in FM radar.
(a) Frequency variation of signals.
(b) Beat frequency of one target.

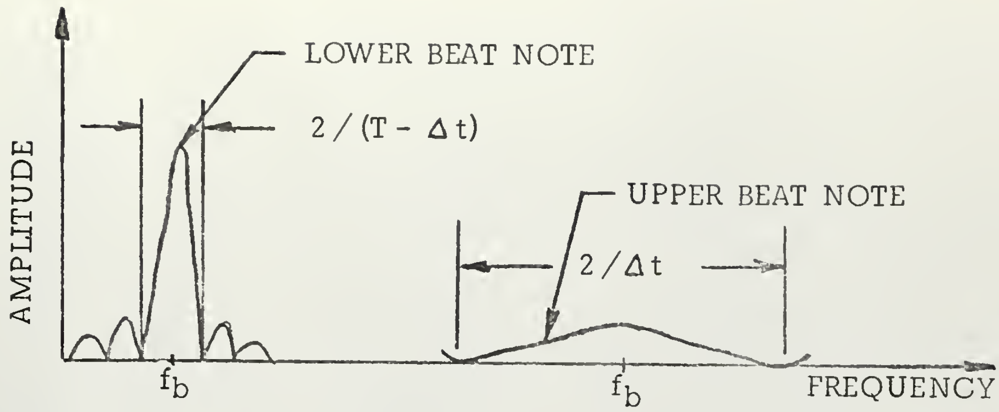

Figure 3.

Distribution of range beat notes.

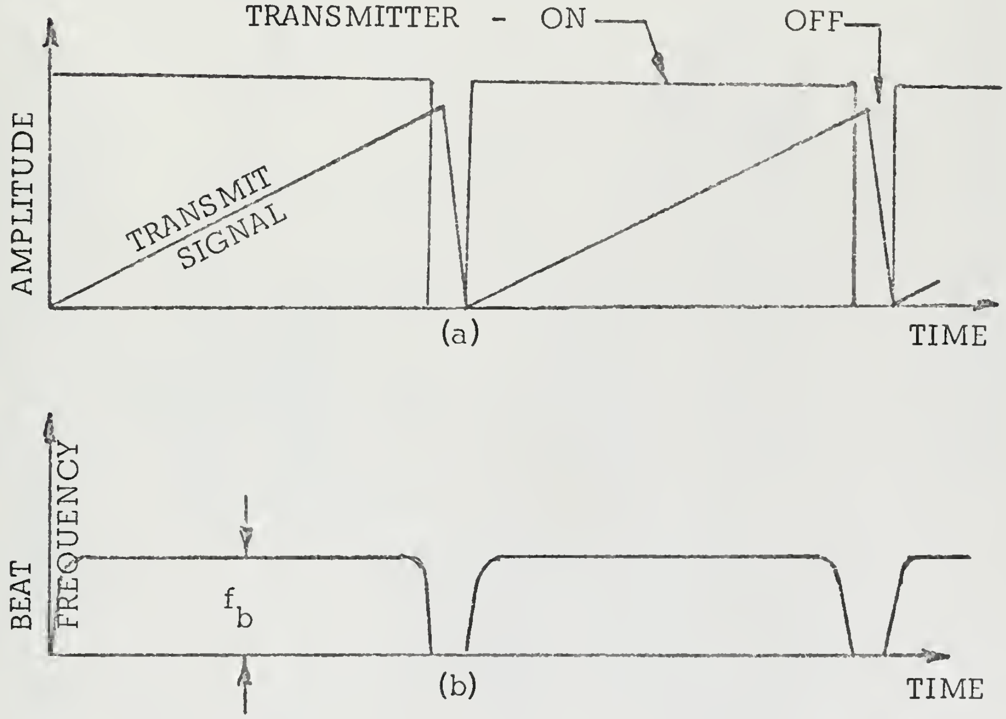

Figure 4.

Method of resolving range ambiguity.
(a) Transmit signal pulsed off during flyback.
(b) Beat frequency of single target.

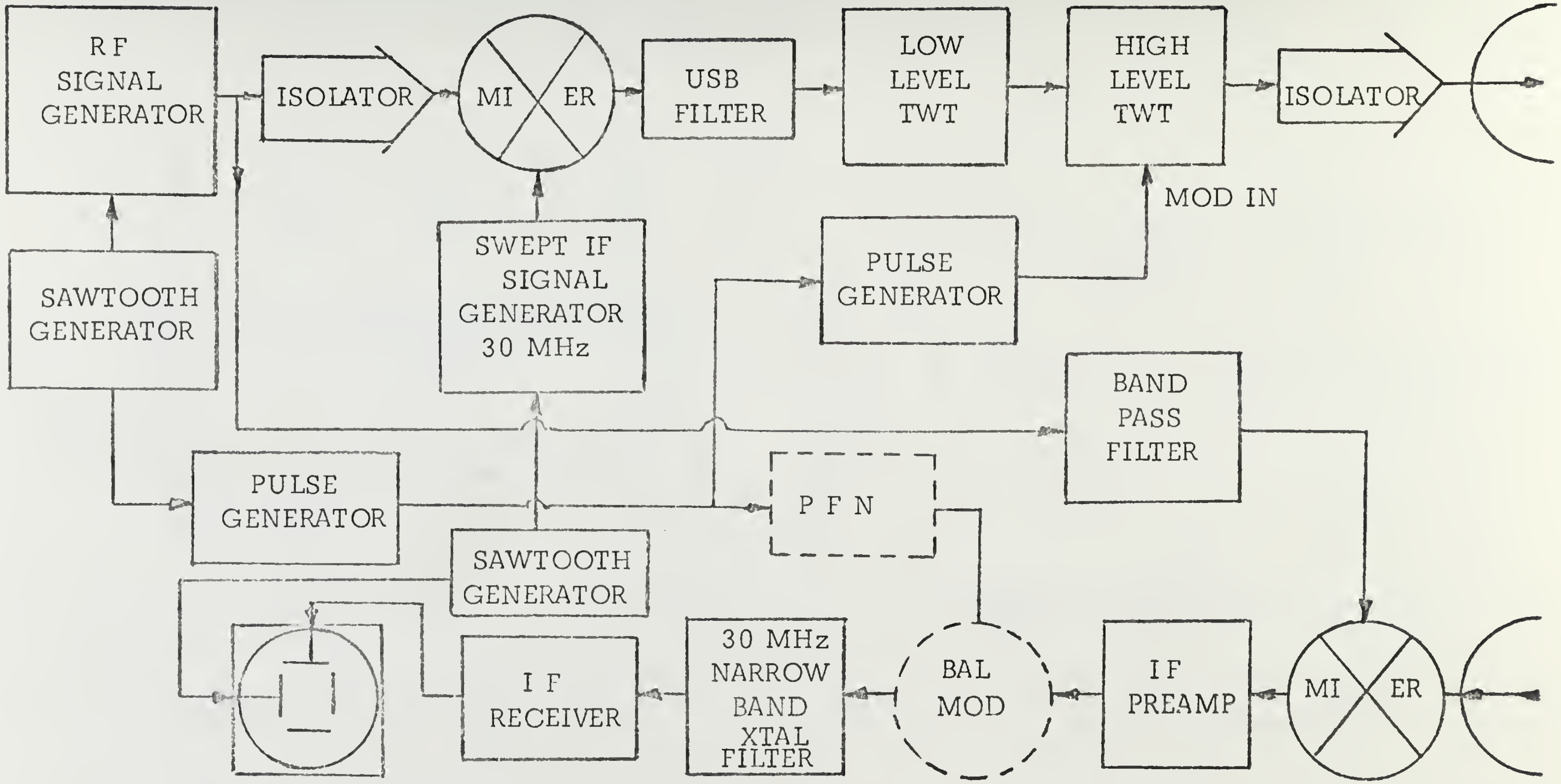

Figure 5.

Block diagram of developmental system.
For equipment listing see Appendix A.

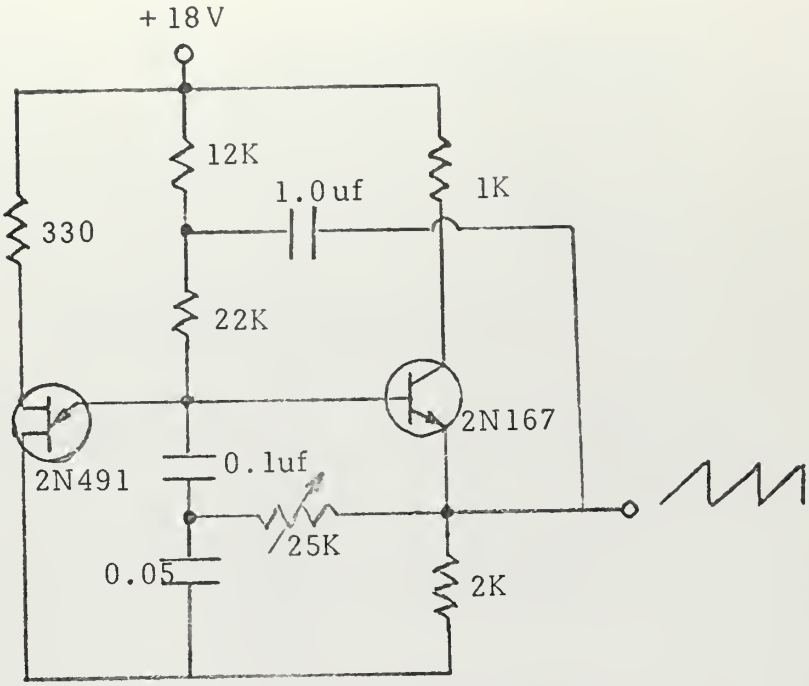

Figure 6.

Sawtooth generator

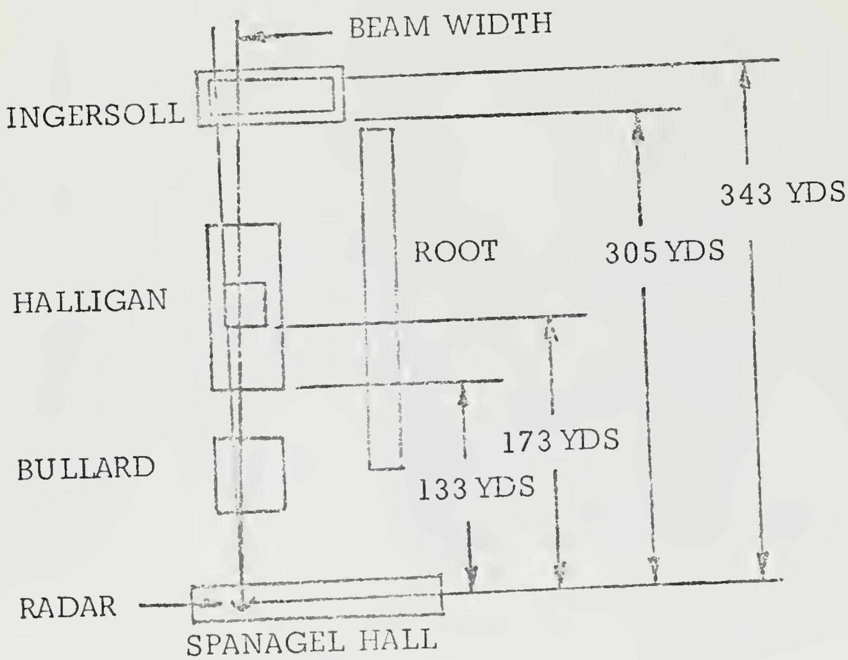

Figure 7.

Map of NPGS

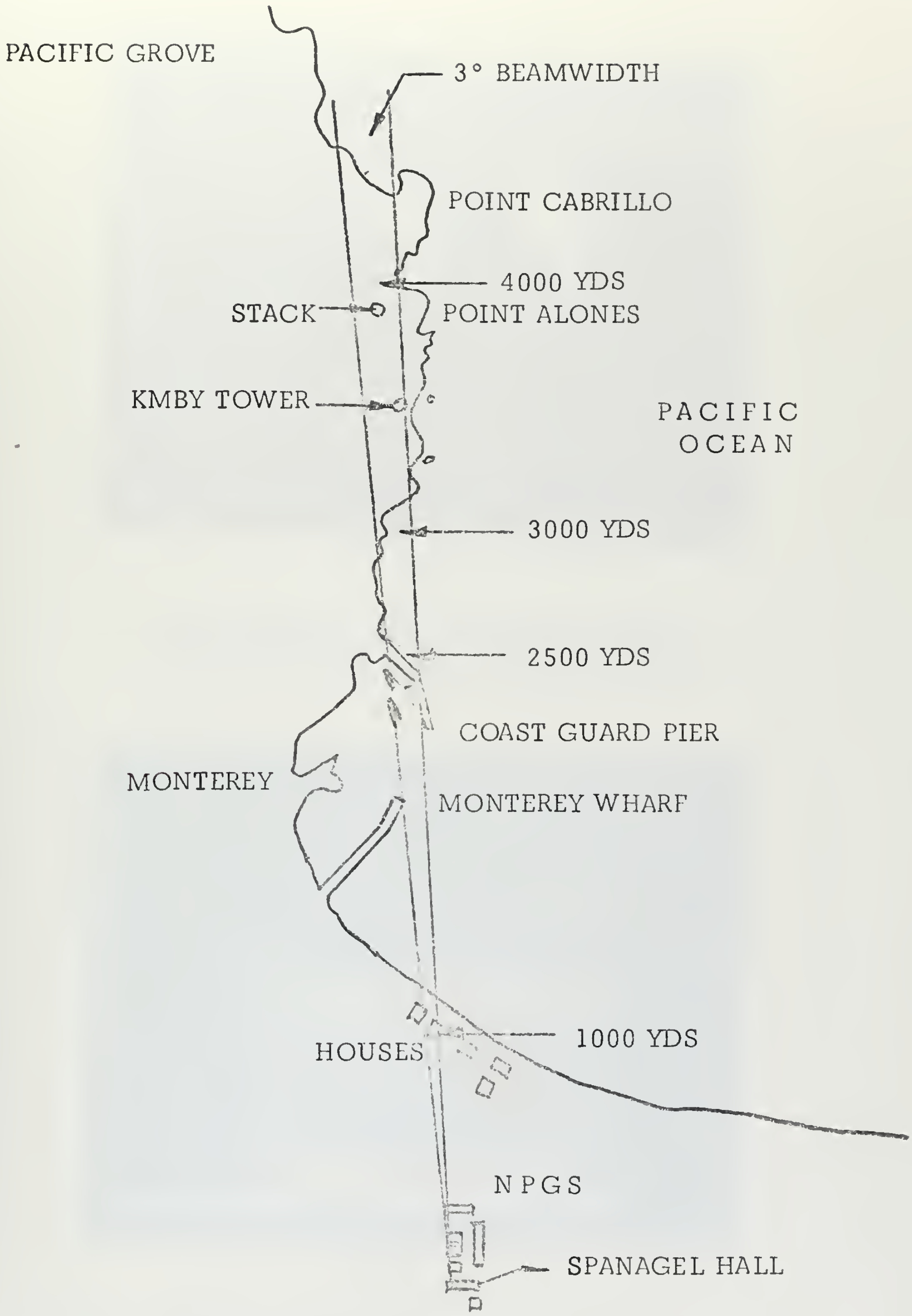

Figure 8.

Map of local area.

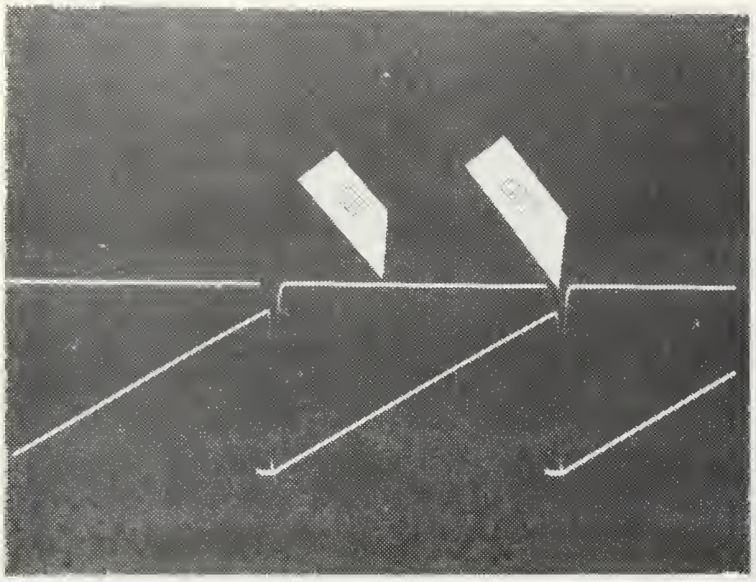

Figure 9.

TWT pulsed off during sawtooth flyback.
Horizontal: 100 microseconds per division.

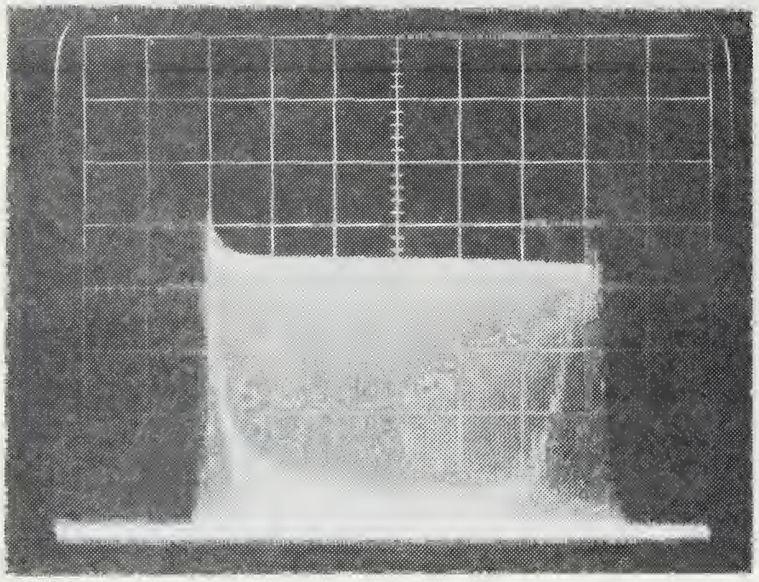

Figure 10.

Transmit spectrum without sawtooth flyback suppressed.
Horizontal: 2 MHz per division.

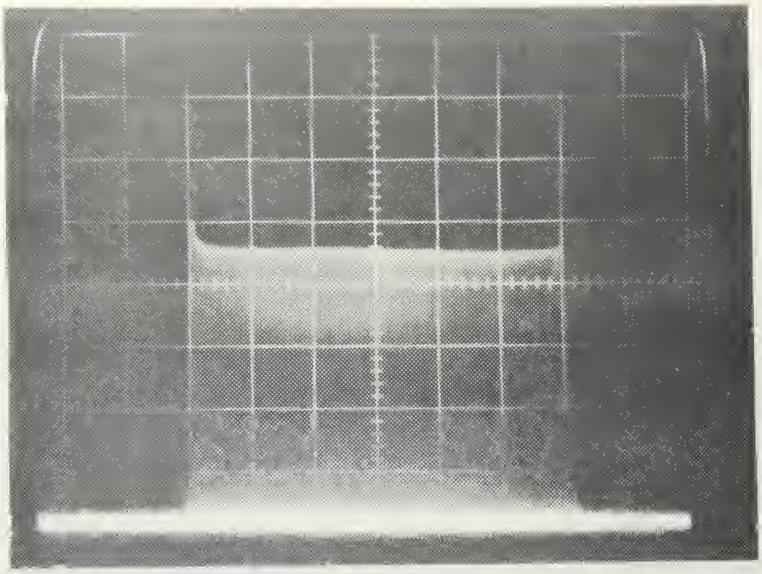

Figure 11.

Transmit spectrum with sawtooth flyback suppressed.
Horizontal: 2 MHz per division.

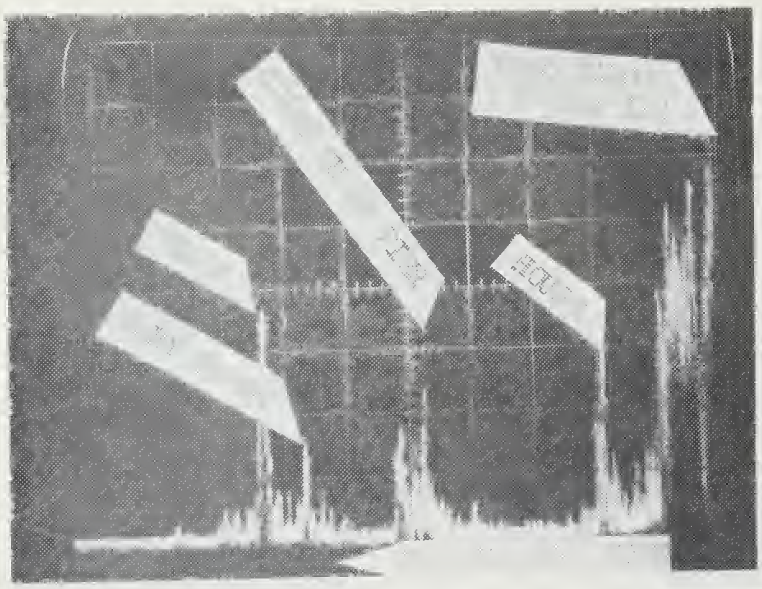

Figure 12.

Radar photograph at long range.
520 yards per division.

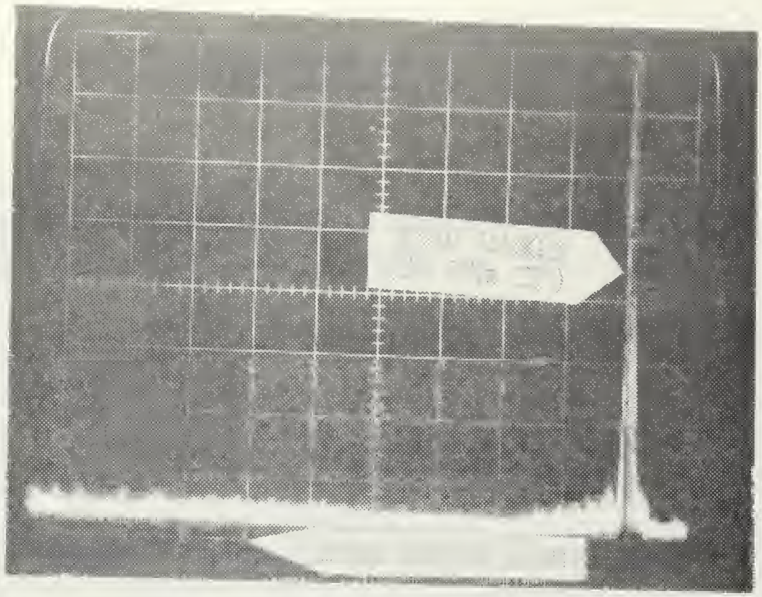

Figure 13.

Radar photograph of the sky.

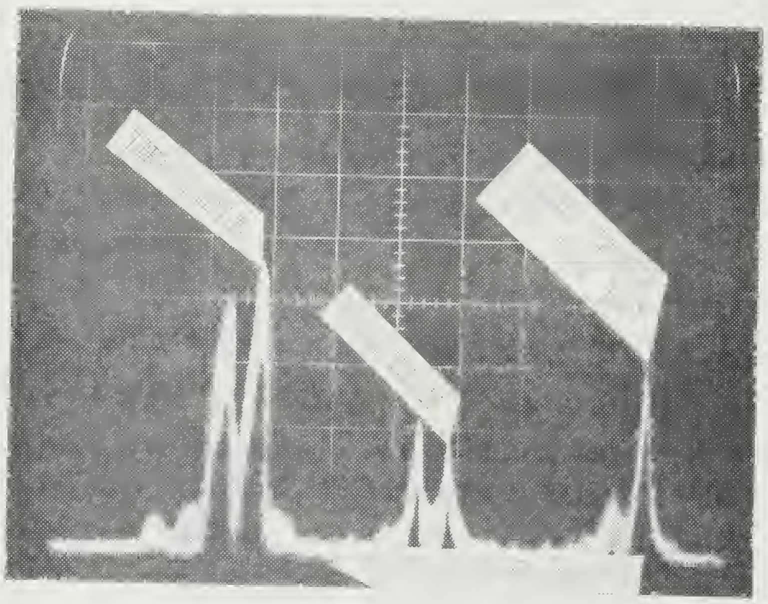

Figure 14.

Radar photograph at short range.
52 yards per division.

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13. ABSTRACT

The feasibility of an X-band (8.0-12.5 GHz) continuous-wave multiple-target radar employing linear frequency modulation was investigated.

From available laboratory equipment a working model was constructed and tested. Separate parabolic antennas were used for transmitting and receiving. The transmitter employs a reflex klystron followed by low and high-level traveling-wave tubes. The receiver utilizes a single narrow-band crystal filter with a swept local oscillator for range search.

Target data acquired with the developmental unit is presented.

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Security Classification

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KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Radar						
Frequency-Modulation						
Continuous-Wave						

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c.1 A developmental CW
FM multi-target radar.